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INTERFERENCE MEASUREMENTS IN THE SPECTRA OF NOBLE GASES

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ABSTRACT

Employing the Fabry-Perot étalon interferometer, the wave lengths corresponding to lines in the first spectra of the noble gases have been measured relative to the fundamental standard of wave length (Cd 6438.4696 A), and to selected red lines of neon previously compared with the primary standard. The observations range from the violet (3948 A) to the infrared (10830 A). Values are given for 3 lines of He, 172 of Ne, 87 of A, 55 of Kr, and 130 of Xe. Many of the lines have been found to be reproducible to eight figures, and are regarded as highly satisfactory standards in spite of objections which have been raised against them on account of isotopic hyperfine structure.

CONTENTS

I. INTRODUCTION

The specification and adoption of international standards of wave lengths for spectroscopy and astrophysics has been one of the functions of the International Astronomical Union since 1922. A wave length of the red radiation from cadmium vapor, evaluated by comparison with the meter, was adopted as the primary standard,[1] and from time to time wave lengths from other sources interferometrically compared with the primary standard by three independent observers have been adopted as secondary standards in various parts of the spectrum. These secondary standards consist mainly of values from the spectrum of the iron arc [2] but include also 24 orange and red lines of neon,[3] and 10 blue lines of krypton.[4] Geissler tubes containing noble gases possess many desirable properties as sources of wave-length standards, and interference measurements in the spectra of these gases have been made at this Bureau since 1911.[5] One or more

[1] Trans. I.A.U. 2, 232(1925).
[2] Trans. I.A.U. 3, 86(1928).
[3] Trans. I.A.U. 2, 41,232(1925).
[4] Trans. I.A.U. 4, 76(1932).
[5] Bul.BS 6,573(1911).

sets of values for the stronger lines of helium,[6] neon,[7] argon,[8] krypton,[8] and xenon [8] have already been published. During the past 2 years new types of photographic emulsions and sensitizers have become available, and following preliminary study of grating spectra,[9] an effort was made to extend the interference measurements in noble gas spectra to include both longer waves and fainter lines than had been observed heretofore. The results of these measurements are reported in this paper.

Before presenting our experimental procedure and results, we shall discuss briefly the status of the primary standard, and the general qualifications of noble gases as sources of standard wave lengths.

In order to correct some divergences found among the methods employed by spectroscopists, the I.A.U. Committee on Standards of Wave Length and Tables of Solar Spectra recommended [10] in 1925 "that the Union adopt provisionally the following specifications for the production of the primary standard of wave length: the primary standard of wave length, λ6438.4696 of cadmium, shall be produced by high voltage electric current in a vacuum tube having internal electrodes. The lamp shall be maintained at a temperature not higher than 320° C. and shall have a volume not less than 25 cubic centimeters. The effective value of the exciting current shall not exceed 0.05 amperes. At room temperature, the tube shall be nonluminous when connected to the usual high voltage circuit."

The Union actually adopted the following specifications: [11]

"L'étalon primaire de longuer d'ondes, λ6438.4696 du cadmium, sera prodiut par un courant électrique à haute tension dans un tube à vide portant des électrodes intérieures. La lampe sera maintenue à une température ne dépassant pas 320° C., et devra donner des différences de marche d'au moins 200,000 longuers d'ondes. La valeur efficace du courant d'excitation ne dépassera pas 0.05 ampere. À la température de la salle le tube ne sera pas lumineux quand il sera connecté au circuit habituel à haute tension."

In 1927 the International Conference on Weights and Measures also adopted the red radiation from cadmium vapor as the primary standard of wave length,[12] but the specifications of the source differ somewhat from those adopted by the I.A.U. "Dans l'état actuel de nos connaissances, il est recommandé que la Conférence adopte, comme étalon fondamental pour la longuer des ondes lumineuses, la longuer d'onde de la radiation rouge émise par la vapeur de cadmium, déterminée par les expériences de MM. Benoit, Fabry et Perot. D'aprés ces expériences, la longuer d'onde de cette radiation est 6438.4696 x 10^{-10} mètre, lorsque la lumière se propage dans l'air sec à 15° (echelle de l'hydrogene), à la pression de 760 mm de mercure, *g* equivalent à 980,665 cm/sec^2, valeur normale de la pesanteur, La lumière doit ètre produite par un courant électrique de haute tension, continu, ou alternatif de fréquence industrielle (a l'exclusion de la haute fréquence), dans un tube a vide ayant des électrodes intérieures. La lamp doit avoir un volume ne dépassant pas 25 cm^3 et un tube capillaire dont le diamètre ne soit pas inférieur à 2 mm; elle doit ètre

[6] Bul.BS 14,159(1917).
[7] Bul.BS 14,765(1918).
[8] BS Sci.Pap.17,193(1921).
[9] BS J.Research 9,121(1932); 10,139(1933); 10,427(1933).
[10] Trans. I.A.U. 2,40(1925).
[11] Trans. I.A.U. 2,232(1925).
[12] 7 Conf. Gen. des Poids et Mesures, 52(1927).

maintenue a une température voisine de 320°, et la valeur du courant qui la traverse ne doit pas excéder 0.02 ampère. A la température ambiante, le tube ne doit pas être lumineux lorsque le circuit à haute tension y est établi."

This specification is based upon the actual tube and operating conditions used for the comparison of the cadmium waves with the meter, and is, therefore, to be preferred.[13] The I.A.U. specification is less restricted, it does not exclude high-frequency excitation, it does not mention the volume or capillary bore of the tube, but requires that it must give interferences with differences of path of at least 200,000 waves. The condition that the interference limit may be 200,000 waves is objectionable since this is less than half of the theoretical or actual limit of the Michelson tube, and cadmium sources in which any such reduction in interference order occurs will certainly yield a different value for the primary standard. Up to the present time the Michelson tube has always been used for the most precise comparisons of wave lengths with meters, and of the secondary standards. The results have justified the retention of the red cadmium line emitted by the Michelson lamp as a reliable standard of length, and indicate that the cadium, neon and krypton scales are identical within 1 part in 50 millions.

It has been variously proposed to substitute the krypton lines 5562 A[14] and 5649 A[15] for the red cadmium line as a primary standard. These lines have relatively low intensity, they involve metastable states of the atom which favor self-reversal, and since krypton lines have been found to show complex hyperfine structure it is doubtful if any of them are suitable as primary standards.[16] The above-mentioned lines of krypton have been examined for hyperfine structure by Romanova and Ferkhmin,[17] who report that Kr 5562 A shows four strong satellites (+0.0020, +0.0040, −0.0016, −0.0033A) and four weak ones (+0.0060, +0.0075, −0.0060, −0.0079A) while Kr 5649 A possess three strong satellites (+0.0014, +0.0034, −0.0020A) and three faint ones (+0.0068, +0.0092, −0.0080A). The same observers claim to have found hyperfine structure in Cd 6438 as emitted by a cooled Schüler tube; they report two strong satellites (−0.0034, +0.0035A) and one faint diffuse one (+0.0092A).

Under extraordinary operating conditions Perard [18] has found a narrow but symmetrical self-reversal in the red radiation from cadmium, and express the opinion that this possibility of reversal renders it unsuitable for use as a fundamental unit of length.

The observations of hyperfine structure and of self-reversal in the red line of cadmium are really beside the point because neither applies to the radiation emitted by the Michelson tube under the conditions specified by the International Conference of Weights and Measures. Under these conditions the line has always been found to be simple, sharp and symmetrical, and comparisons with the meter and with selected lines in the spectra of noble gases have demonstrated that it is reproducible to a very high degree.

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[13] Trans. I.A.U. **4**, 233(1932).
[14] Compt. Rend. **194**,1633(1932).
[15] Phys. Z. **29**,233(1928).
[16] BS J.Research **3**,160(1929).
[17] Compt. Rend. Acad. Sci. USSR Nouvelle serie no. [2]57(1933).
C.R. **198**,727(1934).

According to Aston [19] cadmium had 6 isotopes which in order of intensity have atomic weights 114, 112, 110, 113, 111, and 116. The hyperfine structure of triplet terms in the Cd I spectrum is ascribed by Schüler to a nuclear spin moment of ½ unit for the odd isotopes, and intensity measurements indicate that these constitute 23 percent of all isotopes.[20]

From a study of the polarization of resonance radiation, and Paschen-Back effect, Heydenberg [21] concludes that the separation of the odd isotope levels of $^1P_1$ (final state for 6438 A) is 0.0126 cm^{-1}, the stronger components from the even isotopes fall between these limits and determine the center of gravity, so the red line, even if complex, may be expected to be symmetrical. It may be added that the half width of the red line from cadmium, if the entire width be ascribed to Doppler-Fizeau effect, is 0.005 A, which is in close agree- with 0.006 A measured by Michelson.[22]

With regard to reversibility it is appropriate to look again at the atomic origin of the red line of cadmium.[23] This line represents the transition $5\ ^1P_1 - 5\ ^1D_2$, and the absolute values of the spectral terms are 28,846.60 and 13,319.24, respectively. The normal state of the cadmium atom is represented by $5\ ^1S_0 = 72{,}538.81$, which is 43,692.21 cm^{-1} (nearly 5 volts) lower in energy than $5\ ^1P_1$ so that only cadmium atoms which have been excited by 5-volt electrons are capable of absorbing the red radiation. Furthermore since $5\ ^1P_1$ is not a metastable state it is only under extraordinary conditions that the red line can be observed spontaneously reversed.

Consideration of the above facts leads us to the conclusion that the red radiation emitted by cadmium under the conditions laid down by the International Conference of Weights and Measures remains the most satisfactory fundamental standard of length, and we have accordingly used it again in the wave length measurements in spectra of the noble gases.

Geissler tubes containing noble gases are at present the most convenient and reproducible sources of secondary standards of wave length. When filled with pure gases at low pressure (5 to 15 mm Hg) they emit narrow lines of considerable intensity and if the capillary is viewed side-on it is quite unusual to observe any self-reversal in the lines. Their strongest lines (aside from those in the extreme ultraviolet) lie in the visible and infrared regions and it is especially in the long-wave range that they will be most useful as secondary standards since new types of emulsions and sensitizers have extended the photographic limit of spectroscopy. Aside from hyperfine structure (and Zeeman and Stark effects), the width of spectrum lines excited at low pressure is accounted for by the Doppler-Fizeau effect of the radiating particles, and according to kinetic theory the limiting order of interference (which is a measure of the sharpness of a line), $N = 1.22 \times 10^6 \sqrt{\frac{m}{T}}$ where m is the atomic mass and T the absolute temperature. Since Geissler tubes of the noble gases can be operated at low temperatures, the heavier gases in particular should give exceptionally sharp lines capable of producing interfer-

[19] Phil. Mag. **49**,1191(1925).
[20] Z. Phys. **67**,433(1931).
[21] Phys. Rev. **43**,640(1933).
[22] Travaux et Memoires **11**,143(1895); **15**,7,(1913).
[23] 7. Conf. Gen. des Poids et Mesures, 85(1927).

ence patterns over relatively large paths. This was tested experimentally by Buisson and Fabry [24] who observed the limiting orders of interference for He, Ne, and Kr lines excited at ordinary temperature and at the temperature of liquid air, as reported in table 1.

TABLE 1.—*Limiting orders of interference*

Gass	Atomic mass	Wave-length	Ordinary temperature	(290° K.)	Liquid air temperature	
			N_{obs}	$N_{calc.}$	N_{obs}	$N_{calc.}$
He	4	5,876	144,000	144,000	241,000	249,000
Ne	20	5,852	324,000	321,000	515,000	555,000
A	40			455,000		787,000
Kr	83	5,570	600,000	597,000	950,000	1,033,000
Xe	128			750,000		1,300,000

Reversibility is an important consideration among the credentials of spectral lines as wave length standards. In any spectrum the lines most readily absorbed or reversed are those which involve the final or normal state of the atom. Since the neutral atoms of noble gases in every case have completely filled electron shells (s^2 for He and $s^2\ p^6$ for Ne, A, Kr, Xe, Rn) their normal unexcited states are represented by a $^1S_0$ spectral term. Because of the high stability of these configurations this term corresponds to a relatively large energy and combinations with it are found only in the extreme ultraviolet. The more familiar spectra of the noble gases arise from terms associated with higher quantum states, for example in Ne I the well-known group of yellow, orange, and red lines represent transitions $(s^2\ p^5)\ s-(s^2\ p^5)\ p$ in which the first configuration represents $^1P_1$ and $^3P_{0,\ 1,\ 2}$ (levels s_2, s_3, s_4, s_5, in Paschen's notation),[25] while the second configuration represents a group of more highly excited states. The final states in this case are about 135,000 cm^{-1} above the normal state so that none of these lines would be expected to show spontaneous self-reversal. However, two of the final states, $^3P_0$ and $^3P_2$, on account of the selection rule for inner quantum numbers, cannot combine with the normal state $^1S_0$, and are therefore metastable. Relatively long life of atoms in such metastable states favors absorption by these levels so that neon lines (or any corresponding lines in other noble gases) which are connected with levels s_3 or s_5 in Paschen's notation can exhibit partial reversal,[26] as Meissner proved. The lines connected with the s_2 and s_4 levels on the other hand are relatively free from such effects.

Unfortunately, excepting helium (and perhaps radon, for which no information is available), the spectral lines of the noble gases are afflicted with hyperfine structure of two or more components which impairs any claim which might be made for them as ideal monochromatic standards. This hyperfine structure arises from the isotopic constitution of the noble gases, it can only be eliminated by separation of the isotopes and utilization of a single even-numbered atomic mass. Two types of isotopic fine structure of spectral lines occur, one type

[24] J. de Phys. 2,442(1912).
[25] Ann. Phys. [4]60,405(1919).
[26] Ann. Phys. 76,124(1925).

(isotopic displacement) is displayed by components of even numbered atomic masses (without moments of nuclear spin) and the other (nuclear spin structure) is generally revealed as a coarser pattern of several components associated with each odd-numbered isotope (having moment of nuclear spin).

For the nobles gases the mass numbers in order of the intensities of the mass-spectrum lines are, according to Aston,[27] as given in table 2.

TABLE 2.—*Isotopes of noble gases*

Element	Atomic number	Atomic weight	Mass numbers
He	2	4.00	4.
Ne	10	20.2	20, 22.
A	18	39.91	40, 36.
Kr	36	82.9	84, 86, 82, 83, 80, 78.
Xe	54	130.2	129, 132, 131, 134, 136, 128, 130, 126, 124.

Thus, He spectral lines will be free from isotopic fine structure, Ne and A lines may show one satellite due to the less abundant isotope, Kr lines may consist of a group of components due to even isotopes and an additional pattern arising from the odd isotope, while Xe lines may be expected to be exceedingly complex on account of almost equal abundance of odd and even isotopes, the spin moments of the former and the large number of the latter.

The difficulties which hyperfine structures add to wave length comparisons are, however, much less serious than here implied since mitigating factors are found in the abundance ratios of the isotopes. Thus in Ne the second isotope is only 10 percent of the whole, while in A it is of the order of 1 percent. When observations are made photographically these faint satellites are never detected except with overexposure of the main components and very high resolving power. This explains why the Ne satellites were not discovered until 1927, and also why the A satellites remain hidden at the present time. That such faint satellites can have no appreciable effect on wave-length comparisons is shown by the almost perfect agreement of the values for Ne lines determined at this Bureau [28] before the discovery of Ne isotopes or satellites, with the recent measurements of Jackson.[29] In the former case there was no consciousness of a disturbing factor while in the latter only high resolving powers were found to yield constant values, yet the mean accidental difference between the two sets of values is ± 0.0002 A and the systematic difference is well under 0.0001 A. Similar agreement is found between values of violet krypton lines compared with Ne standards by Humphreys [30] and with Cd 6438 A by Jackson.[31] These matters will be discussed in greater detail in connection with the results presented below.

II. EXPERIMENTAL

The theory of wave-length comparisons with the Fabry-Perot interferometer was first given by Fabry and Buisson,[32] it has become so

[27] I.C.T. 1,45(1926).
[28] Bul.BS 14'765(1917).
[29] Proc. Roy. Soc. [A]143,124(1933).
[30] BS J. Research 5,1041(1930).
[31] Proc. Roy. Soc. [A]138,147(1932).
[32] Astrophys. J. 28,169(1908).

familiar that it is unnecessary to repeat it—reference may be made to a paper by Humphreys,[33] which contains an outline of the methods used also in the reduction of the present observations.

The primary standard was the red radiation from cadmium, emitted from a Michelson tube in accordance with the conditions specified by the International Conference of Weights and Measures. Spectra of the noble gases were obtained from Geissler tubes purchased from Robert Goetze in Leipzig. These tubes were provided with narrow capillaries (about 1 mm bore) to concentrate the luminous discharge and were always used side-on. Cadmium and noble gas tubes were connected in series to the secondary of a transformer which forced a current of 10 to 20 ma through the lamps. For a considerable number of exposures, especially those of longest duration, the neon lamp was used as a source of standards, since the mean of a group of red neon lines is regarded as equivalent to the primary standard.[34] Since the values of neon lines adopted by the I.A.U. are given only to 3 decimals the mean of 4-decimal values determined at this Bureau [35] and by Jackson [36] were adopted for purposes of these recent comparisons.

In order to obviate possible difficulties due to small changes in temperature or barometric pressure which may occur during exposures, alternate exposures of primary and secondary sources were avoided. Both sources were adjusted so as to illuminate the interferometer and spectograph in like manner, and then exposed simultaneously.

The interferometer consisted of silvered quartz plates of 6 cm aperture separated by invar étalons of 3, 6.2, 10, 15, 25, 35, or 43 mm length. The first 2 étalons were employed only for preliminary refinements of wave-length values and for determining the dispersion of phase at reflection by comparison with values obtained from the 43-mm separator.[37]

Two different series of observations were made with the same plates, but the silver films were renewed for the second series. Comparisons with the primary standard constitute part of the second series. Dispersion of phase change at reflection was determined for each silvering and in the second case both before and after the observations since an interval of more than a year had elapsed during which the silver had tarnished considerably. The second determination of phase dispersion checked the first for the longer waves but gave a larger correction in the region of short waves. These corrections must be determined with care if values to 4 decimals are desired for lines which occur several thousand angstroms removed from the primary standard, since even with the highest orders of interference they may amount to as much as a unit in the third decimal place. This is perhaps the most important step in precise measurements of wave lengths by the Fabry-Perot interferometer method. Interference patterns were projected on the slit of the spectrograph by means of achromatic lenses having 25 cm or 50 cm focal length, the short focus lens being used only in connection with the two shortest étalons.

Both a Hilger E_2 spectrograph with glass prism, and a 21-foot concave grating mounted so as to give stigmatic images,[38] were employed

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[33] BS J. Research **5**,1041(1930).
[34] Trans. I.A.U. **2**,41(1925).
[35] Bul. BS **14**,765(1917); J. Opt. Soc. Am. **11**,301(1925).
[36] Proc. Roy. Soc. [A] **143**,124(1933).
[37] Bul.BS **12**,199(1915).
[38] BS Sci.Pap. **18**,191(1922).

as dispersing and recording instruments. The grating was especially useful in the infrared where it separated the patterns of close lines not resolved on the prism spectrograms.

Several different types of photographic plates were tried in making the spectrograms, but all were prepared by the Research Laboratory of the Eastman Kodak Co.[39] In succession, emulsion types I, III, and finally a new type designated by 144, were employed, the last giving the greatest satisfaction on account of increased contrast and greatly reduced graininess. These emulsions were sensitized with one or more of the following Eastman types of sensitizers, F, R, P or Q. Plates sensitized only to the infrared lacked sufficient red sensitiveness to record the primary standard, but this was remedied by adding a little pinacyanol solution to the hypersensitizing bath of dilute ammonia with which all dyed plates are treated just before use.

III. RESULTS

New determinations of wave lengths in the first spectra of the noble gases are presented in 5 tables which follow in atomic order, He, Ne, A, Kr, and Xe. In these tables the whole number in angstrom units appears in the first column and the fractional part in succeeding columns. Values derived from the primary standard (Cd 6438.4696 A) and from the red lines of neon are listed separately, and some of the best data from other sources are added for purposes of comparison. Only the 25 and 35 mm étalons were used in the first, and the values relative to neon are based principally on measurements of spectrograms with the 43 mm étalon. All values are corrected to standard atmospheric conditions by consulting the tables published for this purpose by Meggers and Peters.[40] Unfortunately, since nothing is known about the dispersion of water vapor, it is impossible to calculate the appropriate corrections for humidity, but we can probaby assume that this second-order effect is negligible.

In the tables below only the values for the principal component of complex lines is given, all data on hyperfine structure being omitted. The number of observations is reported with each wave-length value to serve as a rough index of the reliability. Only when the individual determinations with high orders indicate that the probable error of the mean is less than 0.001 A is the fourth decimal retained. The symbol hf means that hyperfine structure has been detected for the line it accompanies.

1. HELIUM

Values for 21 of the most intense He I lines (2945.104 to 7281.349) were determined relative to the primary standard by Merrill.[41] In the infrared, the group at 10830 A was recorded with phosphorophotography by Ignatieff [42] in 1914; it is now within range of ordinary photography and has been measured relative to neon standards. On account of the low atomic mass of He, the lines from uncooled tubes are intrinsically wide and incapable of producing interference patterns with large retardations. With the fixed étalons which were available, the best resolution of the infrared He lines was obtained with separations of 6.2 and 15 mm. The spectrograms were made with the con-

[39] J. Opt. Soc. Am. **21**,753(1931); **22**,204(1932); and Addendum (February 1932).
[40] Bul.BS **14**,724(1918).
[41] Bul.BS **14**,159(1917).
[42] Ann. Phys. [4],**43**,1117(1914).

cave grating, the infrared He lines being recorded in the first-order spectrum on 144–Q plates, and the red Ne standards in the second-order spectrum on III–F plates. Corrections for dispersion of phase between 6400 and 10830 A were avoided in this case by dividing the difference in interference path, 2 (15–6.2), for the first point by the corresponding difference in orders for the second. The results are shown in table 3.

TABLE 3.—He I *interference measurements*

λ air	ν vac	λ Ignatieff
10829.081	9231.866	10829.11±0.02
10830.250	9230.870	10830.32± .01
10830.341	9230.792	

This group represents the transition $^3S_1-{}^3P^0_{0,1,2}$ in which the threefold P term is responsible for 3 lines. The second interval of this term is abnormally small and was not resolved until 1927 when both Hansen [43] and Houston [44] with interferometers of high resolving power and He tubes cooled with liquid air, succeeded in splitting the stronger components of certain visible He lines involving the same $^3P_{1,2}$ levels. The former reported the separations of the ^3P levels as 0.991 and 0.077 cm^{-1}, while our measurements of the infrared group yield 0.996 and 0.078 cm^{-1}. Without doubt these values could be still further improved by observing the infrared lines emitted by a cooled source permitting the use of larger orders of interference.

2. NEON

Beginning with neon, the first spectra of the noble gases become more complex, and in general, are shifted toward longer waves but exhibit the same features in gross structure. An extensive series of Ne wave-length measurements relative to the primary standard was made at this Bureau in 1918.[45] Similar determinations to 4 decimals for 20 yellow, orange and red lines were made in 1933 by Jackson [46] who justifies their use as secondary standards; both sets are quoted in table 4 where they may be compared with our new values. We have succeeded in extending the measurements to longer waves and to fainter lines.

The term structure of the Ne I spectrum was analyzed by Paschen [47] in 1919, and recently extended to include new lines observed in the infrared by Gremmer,[48] and by Meggers and Humphreys.[49]

In 1920 Aston [50] reported ordinary neon to consist of 2 isotopes with mass numbers 20 and 22 in the ratio of 9 to 1, and in 1927 Hansen [51] detected that the strong neon lines (from mass 20) were accompanied on the short wave side by faint satellites (from mass 22). This isotope displacement amounts to −0.02 or −0.03A and

[43] Nature **119**,237(1927); Verh. D. Phys. Ges. **3**,5(1929).
[44] Proc.Nat.Acad.Sci. **13**, 91(1927).
[45] Bul.B.S. **14**,765(1918).
[46] Proc.Roy.Soc. [A] **143**, 124(1933).
[47] Ann. Phys. [4] **60**, 405(1919).
[48] Z. Phys. **50**,716(1928).
[49] BS.J.Research 10, 429(1933).
[50] Nature **104**,334(1927).
[51] Nature **119**,237(1927).

has been studied in detail by Nagaoka and Mishima [52] and by Thomas and Evans.[53] These faint satellites are difficult to detect, and it is apparent from a comparison of the various determinations of wavelength values that they have no appreciable effect on reproducibility or precision of measurement. The uncertainty in value of well determined Ne lines is obviously less than 0.001 A and retention of the fourth decimal place seems justified in such cases.

Perard [54] has reported that certain Ne lines exhibit variable wave length, especially when the orders of interference exceed about 100,000 but we have been unable to confirm such variations. The only line for which we have detected any abnormal behavior is 6402 which appears to be unsymmetrically reversed with étalons of 35 or 43mm length. This line represents the strongest combination with the s_5 level which has the longest metastable life; in Meissner's experiment it was 74 percent absorbed.

TABLE 4.—Ne I *interference measurements*

Structure	λA	Cd standard	Obs.	Ne standards	Obs.	NBS [1] Cd standard	Jackson [2] Cd standard	Structure	λA	Cd standard	Obs.	Ne standard	Obs.	NBS [1] Cd standard	Jackson [2] Cd standard
	4334			125	2				4614			391	4		
	4363			524	3				4617			837	3		
	4381			220	2				4628			309	5		
	4395			556	3				4636			125	4		
	4422			519	5				4636			634	4		
	4424			800	5				4645			416	5		
	4425			400	2				4649			904	3		
	4433			721	3				4656			3923	6		
	4460			175	4				4661			104	5		
	4466			807	4				4670			884	3		
	4475			656	3				4678			218	4		
	4483			190	4				4679			135	4		
	4488			0928	6				4687			671	4		
	4500			182	2				4704			395	5		
	4517			736	3				4708			854	2		
	4525			764	3				4715			344	5		
	4537			751	4				4725			145	4		
	4540			376	4				4749			572	4		
	4552			598	2				4752			7313	6		
	4565			888	4				4758			728	2		
	4573			759	3				4780			338	3		
	4575			060	4				4788			9258	6		
	4582			035	4				4790			218	2		
	4582			450	4				4800			111	3		
	4609			910	4				4810			0625	6		

1 BS Bull. **14**,769(1918).
2 Proc. Roy. Soc. **A143**,131(1933).

52 Proc. Imp. Acad. **5**,200(1929).
53 Phil. Mag. **10**, 128(1930).
54 Compt. Rendi **176**,375(1923); **184**,446(1927).

TABLE 4.—Ne I *interference measurements*—Continued

Structure	λA	Cd standard	Obs.	Ne standards	Obs.	NBS Cd standard	Jackson Cd standard
	4817			636	6		
	4821			924	5		
	4827			338	6		
	4827			587	2		
	4837			3118	6		
	4852			655	5		
	4863			074	5		
	4865			505	4		
	4866			476	2		
	4884			915	5		
	4892			090	4		
	4928			235	3		
	4939			041	4		
	4944			987	4		
	4957			0334	6		
	4957			122	3		
	4994			930	2		
	5005			160	5		
	5011			003	2		
	5022			870	2		
	5031			3484	6		
	5037			7505	7		
	5074			200	6		
	5080			383	6		
	5104			705	2		
	5113			675	5		
	5116	501	1	503	6		
	5122			257	4		
	5144			9376	7		
	5151			963	6		
	5154			422	3		
	5156			664	2		
	5188			612	7		
	5193			130	3		
	5193			224	3		
	5203			8950	7		
	5208			863	3		
	5210			573	3		
	5222			351	5		
	5234			028	3		
	5298			190	5		
	5304			756	2		
	5326			396	2		
	5330	778	2	7766	7	779	
	5341	093	2	091	6	096	
	5343			284	5		
	5355			422	2		
	5360			012	2		
	5374			975	2		
	5400	5620	3	5619	2	5620	

Structure	λA	Cd standard	Obs.	Ne standard	Obs.	NBS Cd standard	Jackson Cd standard
	5433			649	2		
	5448			508	2		
	5562			769	5		
	5656			6585	6		
	5662			547	2		
	5689	817	1	8164	6		
	5719	224	1	2254	6		
	5748	298	1	299	6		
	5764	4182	3	418	6	419	
	5804	450	1	4488	6		
	5820	1553	3	1548	7	155	
hf	5852	4878	8			4880	4876
	5872			828	3		
hf	5881	8950	8			8954	8948
	5902	4634	2	464	4		
	5906			429	3		
	5913			633	4		
hf	5944	8340	8			8343	8343
	5965			474	2		
	5974			628	4		
hf	5975	5343	8			5339	5340
	5987			9069	5		
hf	6029	9968	8			9970	9973
hf	6074	3376	8			3377	3377
hf	6096	1630	8			1630	1630
	6128	4502	2	4513	6		
hf	6143	0627	7			0624	0620
hf	6163	5937	8			5937	5941
	6182			146	3		
hf	6217	2812	8			2811	2814
hf	6266	4952	8			4950	4949
hf	6304	7893	8			7890	7893
hf	6334	4276	8			4280	4280
hf	6382	9914	7			9913	9915
hf	6402	248	4	247	4	2455	2461
hf	6506	5277	7			5278	5280
hf	6532	8824	8			8826	8824
hf	6598	9528	8			9528	9530
hf	6678	2766	8			2760	2766
hf	6717	0430	8			0427	0427
hf	6929	4679	6			4678	
	7024			0508	6		
hf	7032	4125	5	4134	12	4130	
	7059	108	1	109	3		
	7173	9390	5	9389	10		
	7245	1668	6	1668	13		
	7438	8988	6	8990	11		
	7488	8717	5	8722	9		
	7535	774	5	7750	8		
	7544			046	4		

TABLE 4.—Ne I *interference measurements*—Continued

Structure	λA	Cd standard	Obs.	Ne standards	Obs.	NBS Cd standard	Jackson Cd standard	Structure	λA	Cd standard	Obs.	Ne standard	Obs.	NBS Cd standard	Jackson Cd standard
	7943	1802	4	1802	6				8591	2585	5	2584	9		
	8082	4585	2	4580	6				8634	649	4	6480	10		
	8118	549	1	5495	5				8654	383	3	3835	10		
	8136	4058	5	4060	9				8679			491	2		
	8259			380	2				8681			920	4		
	8266	077	2	076	5				8780	6220	5	6223	7		
	8300	3257	5	3258	11				8783	755	5	755	7		
	8377	6070	6	6068	13				8853	864	2	867	5		
	8418	4275	5	4274	9				8865			759	4		
	8495	3604	6	3600	11				9486			680	1		
									9535			167	1		
									9665			424	3		

3. ARGON

An extensive description and analysis of the A I spectrum was published by Meissner [55] in 1916, and recently extended by Rasmussen [56] and by Meggers and Humphreys.[57] The first comparison of A wave lengths with the primary standard were also made by Meissner, [58] and Meggers [59] followed with similar ones. We are now presenting in table 3, new measurements, having observed additional lines and reduced the probable error for many lines to the point where the eighth figure (fourth decimal place) can be given.

Like neon, argon also consists of two (possibly three) isotopes. The mass numbers are 40 and 36 in the ratio of about 160 to 1. Up to the present time no satellites have been reported for A lines and we have not observed them even with overexposures of infrared lines for which the resolving power of a silvered interferometer is very high. On account of the very low intensity of this satellite (due to A^{36}) it is safe to assume that it cannot influence the value of the wave length measured for the strong component (due to A^{40}) under ordinary circumstances. With the same resolving power and type of source, the A I lines appear considerably sharper than Ne I lines, but this is mostly, if not entirely, a consequence of larger atomic mass. However, on account of the relatively high sharpness of argon lines, absence of hyperfine structure due to nuclear spin, and almost ideal freedom from isotopic displacements, it seems probable that among all of the noble gas spectra A I lines will be found best qualified to serve as wave-length standards or standards of length.

[55] Z. Phys. **37**,238 (1926); **39**,172 (1926); **40**,839 (1927).
[56] Z. Phys **75**,695 (1932).
[57] BS J.Research 10,437 (1933).
[58] Ann. Phys. [4] **51**,95 (1916).
[59] BS Sci.Pap.1,198 (1921).

TABLE 5.—*Argon* I *interference measurements*

Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers[1] Cd standard	Meissner[2] Cd standard
	3948			977	4	980	
	4044			4173	6	419	
	4054			5250	3		
	4158	5895	5	5896	4	591	
	4164	1789	3	1788	3	180	
	4181	8825	3	8826	3	884	
	4190	7098	3			714	
	4191	0270	2			027	
	4198	3160	6	316	2	316	
	4200	6738	6	674	2	676	
	4251			1842	3	184	
	4259	3607	5	3603	3	362	
	4266	2855	5	2853	4	286	
	4272	1678	5	1680	4	169	
	4300	1000	5	0995	7	101	
	4333	5601	4	5595	3	561	
	4335	3363	3	3370	3		
	4345			1666	4	168	
	4363			7936	4		
	4423			9936	3		
	4510	7324	5	7322	10	733	
	4522			3216	8	325	
	4589			2884	6		
	4596			0964	8	096	
	4628			4398	8	445	
	4702			3151	8	317	
	4752			9381	4		
	4768			6716	5		
	4876			2596	5		
	4887			9465	5		
	5162			2845	5		
	5187			7458	5		
	5221			270	2		
	5252			786	2		
	5421			346	2		
	5451			650	2		
	5495			8720	3		
	5506			112	(2)[3]		
	5558			702	3		
	5572			548	(2)		
	5606			732	3		
	5650			7034	3		
	5739			517	(2)		
	5834			263	(2)		
	5860			315	(2)		
	5888			592	(2)		
	5912			084	3		
	5928			805	(2)		
	6032			124	(2)	127	
	6043			230	(2)		
	6052			721	(2)		
	6059			373	(2)		
	6105			645	(2)		
	6170			183	(2)		
	6173			106	(2)		
	6416			315	(2)	307	
	6752			832	3	831	
	6965	4304	5	4302	10	429	432
	7030			262	1	250	
	7067	2177	5	2170	12	217	218
	7147	0412	5	0406	7	042	
	7272	9356	5	9357	9	935	
	7372			117	1	119	
	7383	9800	6	9800	13	979	978
	7503	8667	4	8676	12	867	868
	7514	653	4	6510	12	651	648
	7635	1055	6	1053	13	106	107
	7723	761	2	7597	11	758	760
	7724	206	2	2064	11	210	210
	7891			075	1		
	7948	1756	6	1754	13	175	177
	8006	155	2	1556	12	156	158
	8014	785	2	7856	12	784	786
	8053			307	1		
	8103	6922	3	6922	12	693	691
	8115	3095	3	3115	12	307	310
	8264	5210	6	5209	13	522	525
	8408	207	2	208	12	210	216
	8424	646	2	647	12	646	650
	8521	4406	6	4407	13	442	
	8667	9435	6	9430	13		
	9122	9664	6	9660	12		
	9224	498	5	498	10		
	9354			218	8		
	9657			7841	10		
	9784			5010	10		
	10470			051	4		

[1] BS Sci. Pap. 17,198(1921).
[2] Ann.Phys. [4]51,95(1916).
[3] Observed only with 3 mm étalons.

4. KRYPTON

General descriptions and analyses of the first spectrum of Kr have been published by Gremmer,[60] and by Meggers, deBruin, and Humphreys,[61] to which new data for infrared lines were later added.[62] The first interference measurements of krypton wave lengths were by Buisson and Fabry [63] who obtained 5570.2908 and 5870.9172 A for the bright green and yellow lines. Perard [64] measured 5570.2892 and 5870.9154 A. Wave lengths of a considerable number of the stronger lines have been measured with interferometers by Meggers,[65] Humphreys,[66] and Jackson.[67] These values will be found in table 6, together with new data.

Although krypton atoms have a relatively large mass and correspondingly narrow spectral lines, this advantage is offset by the fact that it has at least 6 isotopes including one of odd mass (84, 86, 82, 83, 80, 78 in order of intensity).[68] Sixteen of the stronger Kr lines (4273 to 5870 A) were examined with Lummer-Gehrcke interferometers by Gehrcke and Janicki;[69] they reported that all lines are sharp, especially 5,570 and 5,870 A. According to Perard [70] who studied the latter lines with a Michelson interferometer, each has two close satellites. The hyperfine structure of Kr lines has been studied recently by Humphreys [71] and by Kopferman and Wieth-Knudsen.[72] No isotopic displacements have been detected, but it appears that the components of the even isotopes coincide with the center of gravity of Kr^{83}, and analysis of observed hyperfine structures indicates that a mechanical moment of spin equal to or exceeding 7/2 units must be ascribed to the nucleus of the odd isotope. Fortunately this isotope constitutes only about 12 percent of the whole so that the resolvable satellites contain only a few percent of the total energy in krypton lines.

Table 6.—*Krypton* I *interference measurements*

Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers [1] Cd standard	Humphreys [2] Ne standard	Jackson [3] Cd standard	Structure	λA	Cd. standard	Obs.	Ne standard	Obs.	Meggers [1] Cd standard	Humphreys [2] Ne standard	Jackson [3] Cd standard
	4273	9698	4	9700	6	9696	9705	9702		4410						369	
	4282			9680	4	967	9698	9689		4418						769	
	4286			487	1		4875			4425			190	1		1909	
	4300			487	1		4877			4453	9178	3	9176	6	9174	9183	9179
	4318	5522	2	5526	3	552	5523	5522		4463	6902	3	6901	5	690	6897	6906
	4319	5800	4	5796	8	580	5798	5801		4502	3550	3	3544	5	354	3546	3548
	4351			3602	2		3605			4550						298	
	4362	6424	3	6418	6	6422	6429	6425		4812						607	
	4376	1218	3	1220	8	122	1217	1221	hf	5562	2255	3	2254	4	224	2251	2266
	4399			9667	2	969	9675	9673	hf	5570	2892	4	2893	6	2872	2890	2899

1 BS Sci.Pap. **17**,201 (1921). 2 BS J.Research **51**,047 (1930). 3 Proc Roy. Soc. **A138**,151 (1932).

60 Z. Phys. **73**,620 (1932).
61 BS J.Research **7**,643 (1931).
62 Z. Phys. **73**,779 (1932); BS J.Research **10**, 443 (1933)
63 Compt. Rend. **156**,945 (1913).
64 Compt. Rend. **176**,1,060 (1923).
65 BS. Sci.Pap.**17**,193 (1921).
66 BS J.Research **5**,1,047 (1930).
67 Proc. Roy. Soc. [A] **138**,147 (1932).
68 Proc. Roy. Soc. [A] **126**,521 (1930).
69 Ann. Phys. [4] **81**,314 (1926).
70 Compt. Rend. **184**,447 (1927).
71 BS J.Research **7**,453 (1931).
72 Z. Phys. **85**, 353 (1933).

TABLE 6.—*Krypton* I *interference measurements*—Continued

Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers Cd standard	Humphreys Ne standard	Jackson Cd standard	Structure	λA	Cd. standard	Obs.	Ne standard	Obs.	Meggers Cd standard	Humphreys Ne standard	Jackson Cd standard
	5580			390	1					7746			828	1		831	
hf	5649			5625	2		5627			7854	8217	5	8212	3		823	
	5672			452	1					7913	4246	2	4238	2		443	
	5832			857	1					7928	5998	2	5994	2		602	
	5866			752	1					7982			406	1			
hf	5870	9154	4	9153	3	9137	9153	9167	hf	8059	5038	5	5039	4		5053	
	5993			8506	2				hf	8104	364	1	3642	3		3660	
	6012			158	1				hf	8112	902	1	898	2		9023	
	6056			128	1					8190	0542	5	0544	4		0570	
	6421			0283	2		028			8195			070	1			
	6456			2894	2	290	293			8263	2398	2	2398	3		2412	
	6652			239	1					8272			355	2			
	6699			228	1				hf	8281	049	1	0495	2			
	7224			103	1					8298	1077	2	1077	3		1091	
	7287						262			8412			428	1			
	7486			862	1		850		hf	8508	8701	5	8699	4		8736	
	7587	4132	5	4128	3	414	4135			8764			112	1			
	7601	5444	5	5442	4	544	5465		hf	8776	7490	5	7490	4		7498	
hf	7685	2460	4	2460	2		2472		hf	8928	6922	5	6918	4		6934	
hf	7694	5395	4	5391	3		5401			9751			759	4			

5. XENON

General descriptions and analyses of the first spectrum of xenon were published by Gremmer,[73] and by Humphreys and Meggers.[74] A few of the stronger lines were compared with the primary standard by Meggers [75] in 1917 and a larger number were measured relative to neon standards by Humphreys [76] in 1930. Additional measurements of the latter type were included in the complete description referred to [77] and are reproduced in table 7 after being averaged in some cases with still later observations.

Gehrcke and Janicki [78] were the first to find structure among Xe lines; they examined 42 lines (4,078 to 6,768 A) with Lummer-Gehrcke plates and found 4,501 and 4,734 A to be complex. More recently, hyperfine structure of xenon lines has been studied by Humphreys,[79] by Kopferman and Rindal,[80] and in considerable detail by Jones.[81] In general, Xe line patterns consist of a strong central component together with a number of fainter lines, the total intensity of which is nearly equal to that of the intense central component. The latter represents mainly the unresolved components due to even isotopes with mass numbers 124, 126, 128, 130, 132, 134, 136, which constitute 52.2 percent of the whole. The remaining

[73] Z. Phys. **59**, 154 (1930).
[74] BS J. Research **3**, 731 (1929); **10**, 139 (1933).
[75] BS Sci. Pap. **17**, 193 (1921).
[76] BS J. Research **5**, 1,048 (1930).
[77] BS J. Research **10**, 139 (1933).
[78] Ann. Phys. [4] **81**, 314 (1926).
[79] BS J. Research **7**, 460 (1931).
[80] Z. Phys. **87**, 460 (1933).
[81] Proc. Roy. Soc. [A] **144**, 587 (1934).

components result from the action of moments of spin in nuclei of the odd isotopes, 129 and 131, which respectively account for 27.1 and 20.7 percent of the whole. The observed hyperfine structure indicates that the spin moment $I=0$ for all even isotopes, but $I=\frac{1}{2}$ for Xe ^{129} and $I=3/2$ for Xe ^{131}.

In view of the relatively large abundance of odd isotopes and intensity of hyperfine structure components the Xe I lines appear to be least suited among noble gas spectra as standards. However, if measurements are restricted to the main component, the reproducibility as shown in table 7 is of the same order as for the best lines in other spectra.

TABLE 7.—*Xenon* I *interference measurements*

Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers [1] Cd standard	Humphreys [2] Ne standard	Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers [1] Cd standard	Humphreys [2] Ne standard
	3948			163	2				5394			738	2		
	3950			924	6		925		5439			923	2		
	3967			5411	6		541		5460			037	1		
	3974			417	5				5488			555	1		
	3985			202	4				5552			385	4		
	4078			8202	7		8207		5566			615	4		
	4109			7089	7		7093		5581			784	4		
	4116			1147	7		1151		5618			878	3		
	4135			133	4		123		5688			373	2		
	4193			528	3		5296		5695			750	2		
hf	4203			695	5		6945		5696			477	2		
	4205			404	2				5715			716	2		
	4372			287	3				5716			252	3		
	4383			908	5		9092		5807			311	1		
	4385			768	6		7693		5814			505	3		
hf	4500			978	4	978	9772		5823			890	7		
hf	4524			6805	11	680	6805		5824			800	5		
hf	4582			7472	8	746	7474		5856			509	3		
	4611			8882	7		8896		5875			018	9		
hf	4624	2756	3	2754	4	275	2757		5894			988	9		
hf	4671	2258	3	225	4	225	226		5904			462	2		
	4690			970	4		9711		5922			550	2		
hf	4697			0208	7	020	020		5931			241	8		
hf	4734			1518	4	154	1524		5934			172	8		
hf	4792			619	7		6192		5974			152	2		
hf	4807			0190	7	019	019		5998			115	3		
	4829			708	3	705	709		6007			909	3		
	4843			2934	6		294		6111			761	6		
hf	4916			507	2		508		6111			951	6		
	4923			152	5		1522		6152			070	3		
	5028			2794	8		2785		6163			661	8		
	5162			711	2				6163			935	4		
	5362			244	1				6178			303	5		
	5364			626	1				6179			665	5		
	5392			795	3				6182			420	8		

[1] BS Sci.Pap.17, 202(1921).
[2] BS J.Research, 5, 1,048(1930).

TABLE 7.—*Xenon* I *interference measurements*—Continued

Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers Cd standard	Humphreys Ne standard	Structure	λA	Cd standard	Obs.	Ne standard	Obs.	Meggers Cd standard	Humphreys Ne standard
	6198			260	7				6976			182	2		
	6200			892	2				7119			598	2		598
	6206			297	1				7283			961	1		
	6224			168	2				7285			301	2		298
	6261			212	6				7316			272	2		
	6265			302	5				7321			452	1		
	6286			011	1				7336			480	2		
	6292			649	3				7386			003	2		002
	6318			062	10				7393			793	2		791
	6430			155	1				7584			680	2		680
	6469			705	10			hf	7642			024	3		026
	6472			841	5				7802			651	2		
	6487			765	8				7881			320	1		
	6498			717	7			hf	7887			393	3		3898
	6521			508	2			hf	7967			342	3		341
	6533			159	7				8057			258	3		
	6543			360	4				8061			339	3		
	6554			196	3				8206			336	3		
	6595			561	7			hf	8231	633	3	6336	5		6348
	6632			464	4				8266			520	3		
	6666			965	6			hf	8280	116	5	1162	6		1163
	6668			920	10				8346	8217	3	822	3		823
	6678			972	3			hf	8409	1894	5	1894	4		190
	6681			036	3				8739			372	1		
	6728			008	10			hf	8819	4106	2	4113	5		412
	6827			315	9		315	hf	8952	2509	3	2506	8		254
	6846			613	3			hf	9045	4466	3	4460	7		446
	6866			838	1				9162	653	3	6520	7		654
	6872			107	3				9513			377	3		
	6882			155	5		1543		9799			697	5		
									9923			198	5		

WASHINGTON, June 20, 1934.